

Antiproton-Proton Channels in J/ψ Decays

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(Dated: February 2, 2008)

The recent measurements by the BES Collaboration of J/ψ decays into $\gamma p\bar{p}$ indicate a strong enhancement at $p\bar{p}$ threshold not observed in the decays into $\pi^0 p\bar{p}$. Is this enhancement due to a $p\bar{p}$ quasi-bound state or a baryonium? A natural explanation follows from a traditional model of $p\bar{p}$ interactions based on G -parity transformation. The observed $p\bar{p}$ structure is due to a strong attraction in the 1S_0 state, and possibly to a near-threshold quasi-bound state in the $^{11}S_0$ wave.

PACS numbers: 12.39.Pn, 13.20.Gd, 13.60.Ie, 13.75.Cs, 14.65.Dw

A point of interest in the antiproton interactions is the question of existence or non-existence of exotics in the nucleon-antinucleon ($N\bar{N}$) systems: quasi-bound, virtual, resonant, multiquark or baryonium states [1]. Such states, if located close to the threshold, may be indicated by large scattering lengths for a given spin and isospin state. For this purpose the scattering experiments are apparently the easiest to perform with a good precision. However, a clear separation of quantum states is not easy. Complementary measurements of the X ray transitions in antiprotonic hydrogen are useful to select some partial waves. These are particularly valuable when the fine structure of levels is resolved. Such a resolution has been achieved for the 1S states [2] and partly for the 2P states [3]. Another method to reach selected states are formation experiments. In this way a resonant-like behavior was recently observed by BES Collaboration in the radiative decay

$$J/\psi \rightarrow \gamma p\bar{p} \quad (1)$$

close to the $p\bar{p}$ threshold [4]. On the other hand, a clear threshold suppression is seen in the pionic decay channel

$$J/\psi \rightarrow \pi^0 p\bar{p}. \quad (2)$$

To understand better the nature of the enhancement, one should look into the $p\bar{p}$ sub-threshold-energy region. This may be achieved, indirectly, in the $\bar{p}d$ low-energy scattering or $\bar{p}d$ atoms. Such atomic experiments were performed, but the fine structure resolution has not been achieved so far [5].

The purpose of this letter is to discuss the physics of slow $p\bar{p}$ pairs produced in the J/ψ decays. The J^{PC} conservation reduces the number of $p\bar{p}$ final states to several partial waves. These, denoted by $^{2I+1}2S+1L_J$, differ by their isospin I , spin S , angular momenta L and total

spin J . Close to the $p\bar{p}$ threshold, quite different behavior of scattering amplitudes is expected in different states. In the $1S$ state of antiprotonic hydrogen it is the $^1S_0 = (^{11}S_0 + ^{31}S_0)/2$ and $^3S_1 = (^{13}S_1 + ^{33}S_1)/2$ waves which are studied [2]. While atomic experiments determine the scattering lengths, the BES experiment allows to extend this knowledge into a broad energy region above the threshold. As will be shown, the radiative J/ψ decay involves also the $^{11}S_0 + ^{31}S_0$ combination. The understanding of this and other involved states should be based on the experience gained in studies of elastic and inelastic $N\bar{N}$ scattering. We use the Paris potential model [6, 7, 8, 9] for this purpose.

To our present knowledge, none of the available related works [10, 11, 12, 13, 14] on the J/ψ decays (1) and (2) have given a comprehensive explanation of the BES experimental spectra. Only two of these papers [10, 12] compare their results to the data. The Jülich $N\bar{N}$ model is used in [10] to show that, within the Watson-Migdal approach, the isospin 1 S -wave can reproduce the low energy part of the $p\bar{p}$ spectrum in the radiative decay. The same spectrum is fitted with a constant scattering length in Ref. [12]. The length obtained in this way is larger than the lengths calculated in potential models. In Ref. [11], more realistic but spin averaged constant lengths are shown to generate some low-energy enhancement in reaction (1). A K -matrix, calculated with the one-pion exchange in the Born approximation, is considered in Ref. [14]. An enhancement is seen, but this model is too simple to describe the $N\bar{N}$ interactions. The formation mechanisms in the radiative decays are discussed qualitatively in Ref. [13], where the quantum numbers of final states are listed with the recommendation to look into decay modes of the $p\bar{p}$ systems.

In the present work the following results are obtained. The set of allowed final $p\bar{p}$ states is limited to three partial waves in the photon channel and to two waves in the pion channel. Among the three possible $p\bar{p}$ states in the $p\bar{p}\gamma$ channel one is dominated, at very low energies, by the well known $p\bar{p}(^{13}P_0)$ resonance, formed as a result of attractive one-pion exchange forces. However, this state as well as another allowed 3P_1 state cannot explain the experimental spectrum. The final $p\bar{p}\gamma$ state is dominated by the $p\bar{p}(^1S_0)$ wave. A strong attraction arises in this

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TABLE I: States of low energy $p\bar{p}$ pairs allowed in the $J/\psi \rightarrow \gamma p\bar{p}$ and $J/\psi \rightarrow \pi^0 p\bar{p}$ decays. The first column gives the decay modes to the specified internal state of the $p\bar{p}$ pair. Well established, two particle analogs are indicated in the second column [15]. The third column gives J^{PC} for the light spectator particles, photons or pions. The fourth column gives J^{PC} for the internal $p\bar{p}$ system; the last column gives the relative angular momentum of the light particle vs. the pair. $J^{PC} = 1^{(-)-}$ for J/ψ .

Decay mode	Analog	$J^{PC}[\gamma \text{ or } \pi^0]$	$J^{PC}[p\bar{p}]$	Relative 1
$\gamma p\bar{p}(^1S_0)$	$\gamma\eta(1444)$	1^{--}	0^{-+}	1
$\gamma p\bar{p}(^3P_0)$	$\gamma f_0(1710)$	1^{--}	0^{++}	0
$\gamma p\bar{p}(^3P_1)$	$\gamma f_1(1285)$	1^{--}	1^{++}	0
$\pi^0 p\bar{p}(^3P_1)$		0^{-+}	1^{+-}	0
$\pi^0 p\bar{p}(^3S_1)$	$\pi^0 \rho$	0^{-+}	1^{--}	1

wave as a result of coherent one-pion and two-pion exchange forces. It produces broad, deeply bound states, difficult to detect. However, the recent version of the model [6], adapted to hydrogen atom data, generates a near-threshold state in the related $p\bar{p}(^1S_0)$ wave. This state is about 50 MeV wide and bound by 5 MeV.

In the $p\bar{p}\pi^0$ decay channel, isospin being conserved, two $p\bar{p}$ waves, 3S_1 and 3P_1 , are allowed. These indicate distinctly different threshold behavior. The S wave is ruled out by the experiment and the $p\bar{p}(^3P_1)$ leads to a natural explanation of the BES spectrum. These findings can be unified in a qualitative model for both decay modes.

The allowed final states. The J^{PC} conservation limits the number of slow $p\bar{p}$ final states. The latter are understood as $p\bar{p}$ pairs with small $M_{p\bar{p}} - 2m_p$ where $M_{p\bar{p}}$ is the pair invariant mass. The allowed states are listed in Table I and a few possibilities exist for each channel.

The BES experiment provides an angular distribution for the photons. The specific situation of e^-e^+ collision is that the projectiles are polarized perpendicular to the beam direction and the J/ψ spin direction follows that of the beam. The angular distribution can be measured within a limited range. It offers a hint which in principle permits to further reduce the number of allowed final states. For completeness, the angular distributions of the photon in the states of interest is calculated below. The simplest Lorentz invariant couplings which are also gauge invariant are given in Table II. The $p\bar{p}$ pair is described as a single scalar (3P_0), pseudoscalar (1S_0) or pseudovector (3P_1) particle. This picture is expected to work for the pairs of small center of mass (CM) system energies. Next, the appropriate couplings are reduced to the J/ψ CM system and the corresponding angular distributions are calculated. The couplings given in Table II follow from Hamiltonians that couple the electromagnetic field $f_{\sigma\rho}$ to the J/ψ field $F_{\sigma\rho} = \partial_\sigma V_\rho^J - \partial_\rho V_\sigma^J$ and to the corresponding scalar φ^s , pseudoscalar φ^{ps} and pseudovector φ_σ^{pv} fields describing the low energy $p\bar{p}$ pairs. These gauge invariant Hamiltonians are $H^s = (e\kappa^s/2M_J) \int f_{\sigma\rho} F^{\sigma\rho} \varphi^s$,

$H^{ps} = (e\kappa^{ps}/4M_J) \int \tilde{f}_{\sigma\rho} F^{\sigma\rho} \varphi^{ps}$ [16] and $H^{pv} = e \int f_{\sigma\rho} V_\alpha^J \varphi_\beta^{pv} \varepsilon^{\sigma\rho\alpha\beta}$, where $\kappa^{s,ps}$ are the magnetic moments for the transitions. The vector nature of the fields, expressed by $\nabla^\beta \varphi_\beta^{pv} = 0$, leads to the results given in Table II. The first two angular distributions are well known [17]. θ denoting the angle between the γ emission and the beam direction, the angular distributions $(\cos^2 \theta + 1)$ and $\sin^2 \theta$ were tested against the data in Ref. [4]. These have indicated a preference for the first choice, i.e. radiative transitions to 3P_0 or 1S_0 states. However, as can be seen in Table II, a transition to 3P_1 state is not excluded.

Final state interactions. Any multichannel system can be conveniently parameterized by a K -matrix which guarantees unitarity of the description. The transition amplitude from a channel i to a two-body channel f may be presented in the form

$$T_{if} = \frac{A_{if}}{1 + iqA_{ff}} \quad (3)$$

where A_{if} is a transition length, A_{ff} is the scattering length in the channel f , and q is the momentum in this channel (see e.g. [18]). Both lengths can be expressed in terms of energy dependent K matrix elements. The same formalism describes the scattering amplitude in the channel f as

$$T_{ff} = \frac{A_{ff}}{1 + iqA_{ff}}. \quad (4)$$

In the process of interest the formation amplitude A_{if} is unknown, but A_{ff} is calculable in $N\bar{N}$ interaction models constrained by other experiments. For slow $p\bar{p}$ pairs the final state interactions in the $\pi^0 p\bar{p}$ and $\gamma p\bar{p}$ systems are dominated by interactions in the $p\bar{p}$ sub-system. A formal manipulation of Eqs. (3) and (4) yields

$$T_{if} = \frac{A_{if}}{A_{ff}} T_{ff} = \left(\frac{A_{if} q^L}{A_{ff}} \right) \left(\frac{T_{ff}}{q^L} \right), \quad (5)$$

which defines a quantity $C_{if} \equiv A_{if} q^L / A_{ff}$. For S -waves, the standard final state dominance assumption (Watson-Migdal) is equivalent to a weak energy dependence in C_{if} . This is usually true in a small energy range where the denominator in Eq. (3) provides all the energy dependence. In the $p\bar{p}$ states such an approximation is correct for q up to about 0.5 fm^{-1} . It fails at higher momenta since A_{ff} is energy dependent. On the other hand A_{if} stems from a short range $c\bar{c}$ annihilation process. The annihilation range is of the order of $1/m_c$ [19] and only a weak energy dependence is expected in A_{if} . We assume $A_{if} = A_{if}(0) / [1 + (r_o q)^2]$ with a range parameter r_o well below 1 fm. For P -wave final states, the low-energy behavior gives $A_{if} \approx A_{if}^1 q$, $A_{ff} \approx A_{ff}^1 q^2$ where the A_{if}^1 are parameters and the A_{ff}^1 the scattering volumes. The latter are energy dependent as a result of medium ranged π exchange forces. This dependence is particularly strong in those waves which involve resonances. The Watson approximation is not appropriate

TABLE II: Radiative couplings of low energy $p\bar{p}$ pairs to $\gamma J/\psi$ and angular distributions of the final photon with respect to the J/ψ spin direction, J denotes the J/ψ and h the $p\bar{p}$ pair. The second line specifies the transformation property of $p\bar{p}$ pair. The third line gives the invariant couplings and the fourth line presents these in the J/ψ center of mass. $k_\alpha^{\gamma,J,h}$ are the four momenta and $\epsilon_\alpha^{\gamma,J,h}$ the polarization four-vectors of the corresponding fields. The last line gives the angular distributions for the three different cases. The photon energy is denoted by ω , that of $p\bar{p}$ pair by E_h and the J/ψ mass by M_J . For $E_h = 2m_p : \omega/E_h = 0.46$.

decay mode	$\gamma p\bar{p}(^1S_0)$	$\gamma p\bar{p}(^3P_0)$	$\gamma p\bar{p}(^3P_1)$
$h(p\bar{p})$	pseudoscalar	scalar	pseudovector
coupling	$\varepsilon^{\alpha\beta\sigma\rho} k_\alpha^\gamma \epsilon_\beta^\gamma k_\sigma^J \epsilon_\rho^J / M_J$	$(k_\sigma^J \epsilon_\rho^J - k_\rho^J \epsilon_\sigma^J) F_{\sigma\rho}^\gamma / M_J$	$\varepsilon^{\alpha\beta\sigma\rho} k_\alpha^\gamma \epsilon_\beta^\gamma k_\sigma^J \epsilon_\rho^h$
coupling in CM	$(\epsilon^J \wedge \epsilon^\gamma) \cdot \mathbf{k}^\gamma$	$\omega \epsilon^J \cdot \epsilon^\gamma$	$(\epsilon^J \wedge \epsilon^\gamma) \cdot [\mathbf{k}^\gamma (\mathbf{k}^h \cdot \epsilon^h) / E^h - \epsilon^h \omega]$
angular profile	$1 + \cos^2 \theta$	$1 + \cos^2 \theta$	$2 \sin^2 \theta + [(1 + \omega/E^h)/(1 - \omega/E^h)](1 + \cos^2 \theta)$

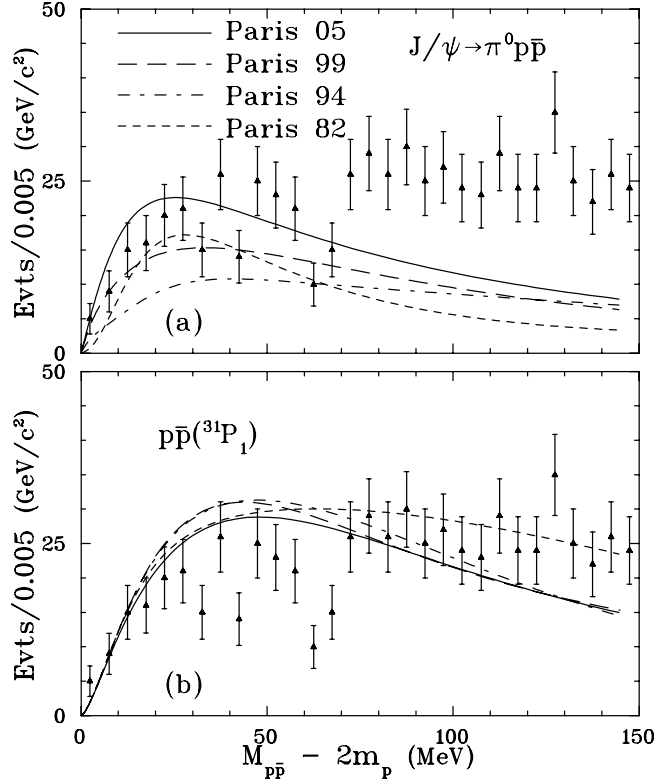


FIG. 1: $\pi^0 p\bar{p}(^3P_1)$ decay channel. Experimental data have been extracted from Fig. 2(a) of Ref. [4]. (a) Final state factor $q |T_{ff}/q|^2$ (Watson approximation). Constant C_{if} of Eq. (5) is chosen to fit the low-energy part of the data. Four versions of the Paris potential model [6, 7, 8, 9] are used. This approximation fails for $M_{p\bar{p}} - 2m_p > 40$ MeV ($q > 1$ fm $^{-1}$). (b) The rate $q |T_{if}|^2$ of Eq. (3). Constant $A_{if}^1(0)$ and formation range parameter $r_o = 0.55$ fm are chosen to obtain a good fit to the data. All four potentials give equivalent fits, even though a 118 MeV wide state bound by 15 MeV is generated in version [6] in the 3P_1 wave.

there, and Eq. (3) must be used. The transition length is parameterized as $A_{if} = A_{if}^1(0)q/[1 + (r_o q)^2]^2$.

The advantage of K matrix formalism is clear in the analyzes of low-energy final state interactions since it isolates the kinematic singularity into a definite form given

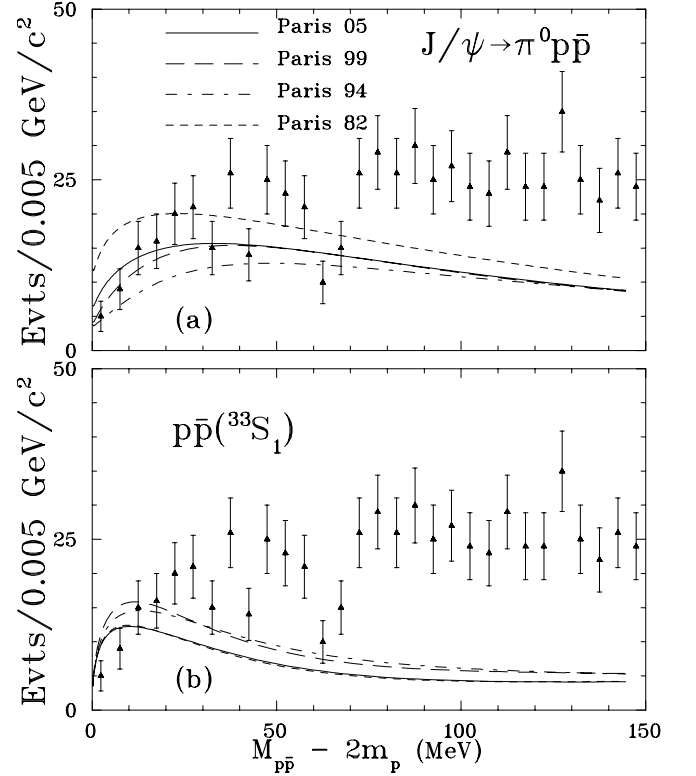


FIG. 2: $\pi^0 p\bar{p}(^3S_1)$ decays. Data as in Fig. 1. (a) Final state factor $q |T_{ff}|^2$ of Eq. (5). (b) Rate $q |T_{if}|^2$ of Eq. (3). This wave is not consistent with the BES data whatever the choice of $p\bar{p}$ potential version, of C_{if} in (a) or $A_{if}(0)$ and r_o in (b).

by Eq. (3). The two functions A_{ff} and A_{if} depend only on q^2 . Hence, close to the threshold, a constant scattering length approximation in Eq. (5) may well indicate some sub-threshold phenomena. This approximation has been used in Refs. [11, 12]. In the $p\bar{p}$ system the energy dependence in A_{ff} is strong as pointed out in Ref. [10] on the basis of an one-boson exchange version of Bonn potential. A similar behavior is seen with the Paris model although these two potentials differ strongly in the two-pion sector. As shown below, Eq. (5) with a constant C_{if} and realistic $A_{ff}(q^2)$ describes a too narrow energy range. The selection of the best $p\bar{p}$ partial wave

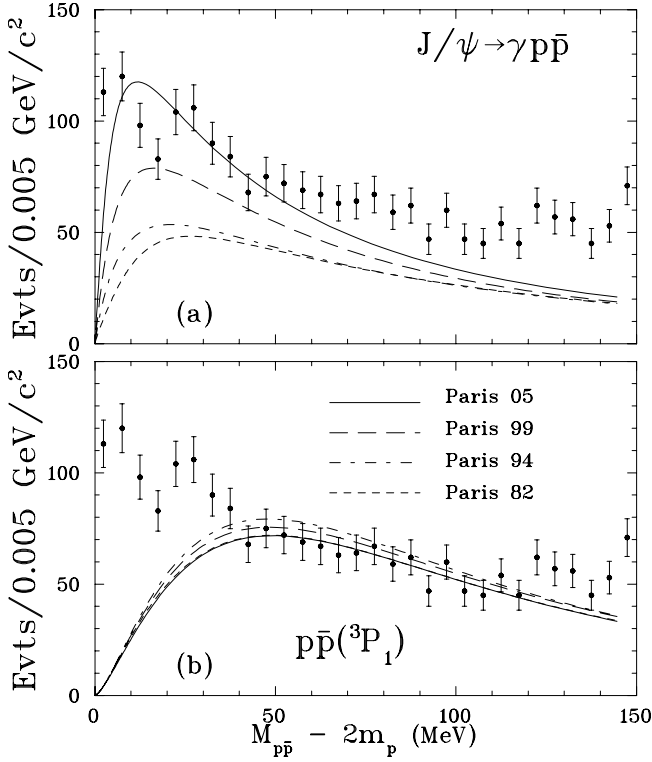


FIG. 3: $\gamma p\bar{p}(^3P_1)$ decays. Experimental data have been extracted from Fig. 3(a) of Ref. [4]. (a) Final state factor $q |T_{ff}/q|^2$ of Eq. (5). The enhancement in Paris 05 solution [6] is related to a 18 MeV wide state bound by 5 MeV in the $^{33}P_1$ wave. (b) Rate $q |T_{if}|^2$ of Eq. (3). This wave cannot reproduce the BES data whatever the choice of $p\bar{p}$ potential version, of C_{if} in (a) or $A_{if}^1(0)$ and r_o in (b).

requires Eq. (3). This equation offers also an explicit and unique dependence on the on-shell A_{ff} (or T_{ff} since $1/(1 + iqA_{ff}) = 1 - iqT_{ff}$). An off-shell A_{ff} may be involved in A_{if} if one attempts to construct a model for the $p\bar{p}$ formation.

Results. There exists substantial phenomenological control over A_{ff} . Here these scattering lengths are calculated in terms of the Paris $N\bar{N}$ potential model and the same procedure is applied to both decay modes $J/\psi \rightarrow \pi^0 p\bar{p}$ and $J/\psi \rightarrow \gamma p\bar{p}$. Figures 1 to 5 present the results obtained with Eq. (5) and Eq. (3) for the five states of interest calculated for the four versions of Paris model [6, 7, 8, 9] which evolved over the last 20 years. This evolution followed the increasing data basis. The last version [6] is based on 3934 data which includes the recent antiproton-hydrogen widths and shifts [2, 3] and the total $\bar{n}p$ cross sections of Ref. [20]. The Coulomb interactions yield enhancements of the S waves at very low energies due to Gamov factors. These affect the final state interaction for $q < 0.15 \text{ fm}^{-1}$ and produce spikes. Since the amplitudes are weighted by the phase space factor q , these become unessential. The q factor represents a residual piece of the full three-body phase space [15].

A qualitative model. As exemplified by the final state

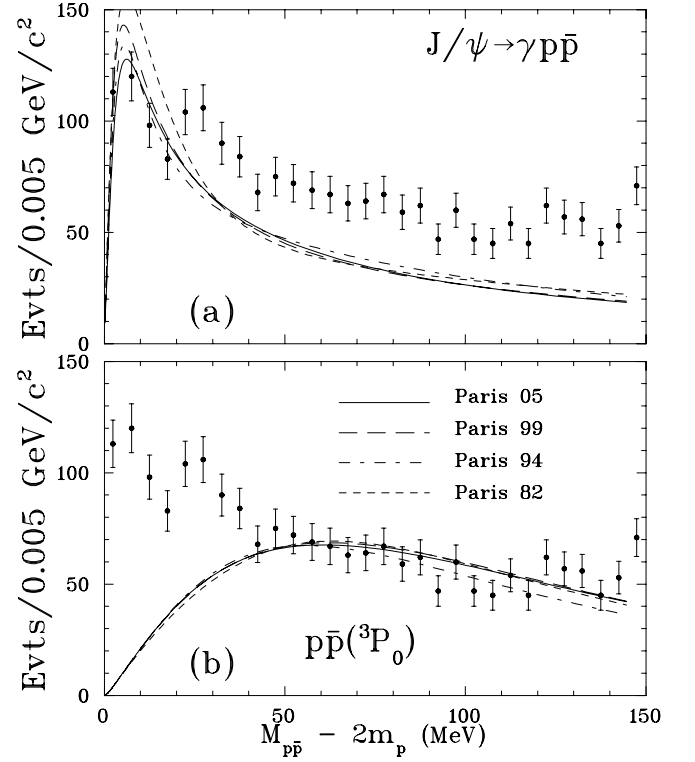


FIG. 4: $\gamma p\bar{p}(^3P_0)$ decays. Data as in Fig. 3. (a) Final state factor $q |T_{ff}/q|^2$ of Eq. (5). The low energy part is dominated by the resonance in the $^{13}P_0$ wave at 1876 MeV, of 10 MeV width, present in all models. However, for $q > 1 \text{ fm}^{-1}$ this approximation fails to fit the data. (b) Rate $q |T_{if}|^2$ of Eq. (3) with $r_o = 0.55 \text{ fm}$. This rate can describe only the $q > 1 \text{ fm}^{-1}$ part of the spectrum. This wave is not consistent with the BES data.

calculations, the BES findings are most consistent with a $p\bar{p}(^1P_1)$ wave in the $\pi^0 p\bar{p}$ channel and a $p\bar{p}(^1S_0)$ wave in the $\gamma p\bar{p}$ channel. Therefore the experiment leads us to a simple picture for the slow $p\bar{p}$ formation.

The initial heavy $c\bar{c}$ quarks in the J/ψ state of $J^{PC} = 1^{--}$ annihilate into a $N\bar{N}$ pair. As argued in Refs. [19, 21] that process is mediated by three gluon exchange. Due to isospin conservation, the baryon pair is formed in an $I = 0$ state of $n\bar{n} + p\bar{p}$ as indicated by experiment [22] and calculations of Ref. [19]. The pair inherits the J/ψ quantum numbers $J^{PC} = 1^{--}$ and forms a 3S_1 state. Next, the emission of a pion or a photon takes place. The π_0 emission proceeds via the standard $\pi N\bar{N}$ coupling $(f_{\pi NN}/2m_\pi) \mathbf{q} \cdot \boldsymbol{\sigma}$. It requires one nucleon to flip spin and change angular momentum, which leads to the final $p\bar{p}(^1P_1)$ state. The photon may be produced as a magnetic one or as an electric one. The relevant formation amplitudes are given by the transition operator $(e/2m_p) [2 \boldsymbol{\epsilon}^\gamma \cdot \mathbf{q} + \mathbf{i} \boldsymbol{\sigma} \cdot (\mathbf{k}^\gamma \times \boldsymbol{\epsilon}^\gamma)]$. In the final states q is small. In the intermediate states it is not necessarily so, but any formation mechanism would favor small momenta. Since $|\mathbf{k}^\gamma|$ is large we conclude that it is the magnetic transition which is more likely to occur. It fa-

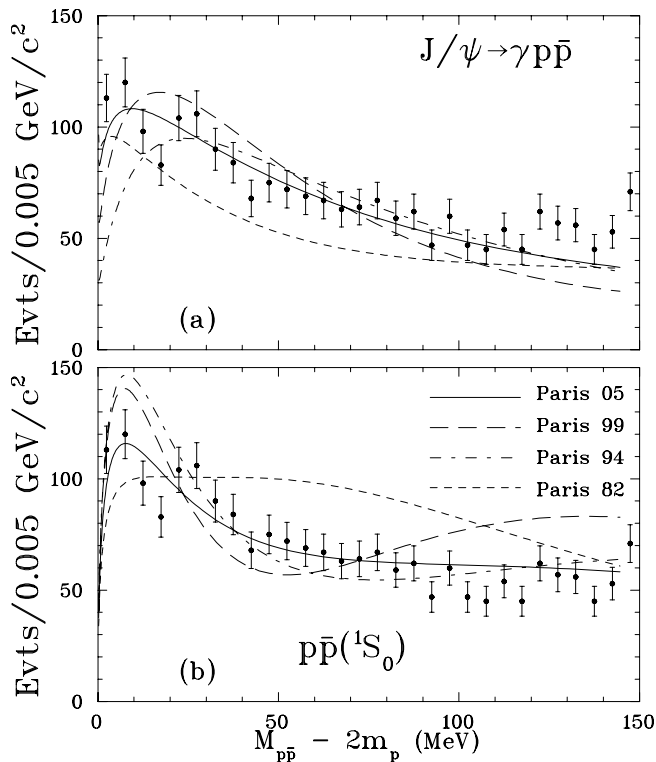


FIG. 5: $\gamma p\bar{p}(^1S_0)$ decays. Data as in Fig. 3. (a) Final state factor $q |T_{ff}|^2$ of Eq. (5). At higher ($q > 2 \text{ fm}^{-1}$) momenta this approximation begins to fail. (b) Rate $q |T_{if}|^2$ of Eq. (3) with $r_o = 0.55 \text{ fm}$. The latest Paris model [6] offers the best fit to the data with an 1S_0 wave involving a quasi-bound state located very close to threshold, of 53 MeV width and 5 MeV binding.

vors formation of the final $\gamma p\bar{p}(^1S_0)$ state which arises in a most natural way. In the initial $p\bar{p}(^3S_1)$ wave, the proton and antiproton magnetic moments are opposite and the transition to $p\bar{p}(^1S_0)$ involves spin and magnetic moment flips. Large moments create large radiative amplitudes. The emission model indicated above, yields comparable branching ratios of the γ and π^0 channels, as found in the experiment. This ratio follows roughly the ratio of the coupling constants $f_{\pi NN}^2 / (4e^2) \approx 2.8$ while the experimental ratio is ≈ 3 [15].

The final $p\bar{p}$ state involves the isospin 1 plus isospin 0 combination. The pair may be also formed in the $n\bar{n}$ state and undergo a transition to $p\bar{p}$ in the final state. That process is expected to be suppressed, since that transition implicates the $T_{ff}(I=1) - T_{ff}(I=0)$ amplitude which is about an order of magnitude smaller than the elastic

$T_{ff}(I=1) + T_{ff}(I=0)$ one. The simple model of final photon radiation discussed above would reduce the neutron channel even further, due to different charges and magnetic moments.

Conclusions. We have shown that the new results of the BES Collaboration find a natural explanation in a fairly traditional model of $p\bar{p}$ interactions based on G -parity transformation, dispersion theoretical treatment of two pion exchange and semi-phenomenological absorptive and short range potentials. This model predicts quasi-bound states close to the threshold, in particular in the $p\bar{p}(^3P_1)$ and $p\bar{p}(^1S_0)$ waves and a resonance in the $p\bar{p}(^13P_0)$ wave. The first two indicate a strong dependence on the model parameters and, so far, are not confirmed in other experiments. The third one, the resonant state, is well established.

It is the 1S_0 state which reproduces the $\gamma p\bar{p}$ spectrum found by the BES collaboration. This wave is dominated by a strong attraction due to the pion exchange forces. This attraction generates broad, deeply bound states. The recent atomic and scattering data indicate that such a state in the 1S_0 wave is located close to the threshold. The BES data offer some support for the existence of such a state. The actual energy level and its width are affected by interactions at distances less than 1 fm. These are not fully understood and only partly controlled through phenomenology.

In order to better see the nature of the 1S_0 state, one should look directly under the $p\bar{p}$ threshold. This could be done with measurements of the invariant mass of few meson systems coupled to $p\bar{p}$ just below the threshold. The selectivity in partial waves is necessary, and a convenient way to reach that is the $J/\psi \rightarrow \gamma \text{ mesons}$ decay. Another, indirect method is to achieve a fine resolution of energy levels in antiprotonic atoms. Some anomalies were found in atoms with nuclei characterized by weakly bound valence protons [23]. These anomalies may reflect a resonant behavior of the $p\bar{p}$ scattering amplitudes in the region of $p\bar{p}$ quasi-bound states. More systematic measurements are necessary to pinpoint the $p\bar{p}$ wave responsible for these effects.

We acknowledge useful discussion on the angular distribution with J.-M. Levy and W. Kloet. We thank M. Lacombe and B. El-Bennich for helpful collaboration on the $p\bar{p}$ Paris potential. B. L. is grateful to S. Jin and P. N. Shen for important informations and enlightening comments. This work was performed in the framework of the IN2P3-Polish Laboratories Convention.

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